

- (10) Using assumed values of K_{11} and K_{∞} and an experimental value of C_A , eq 7 is solved for a C_B value. These values of equilibrium constants and monomer concentrations are used in eq 6 to calculate a value of Δf_A to compare with Δf_A (experimental). A nonlinear least-squares technique based on the Marquardt algorithm (D. W. Marquardt, *J. Soc. Ind. Appl. Math.*, **11**, 431 (1963)) is used to determine optimum values of K_{11} and K_{∞} . The computer program was written by Dr. E. L. Enwall of the University of Oklahoma.
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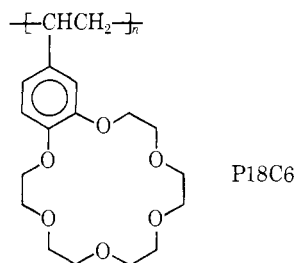
Poly(crown ether) Catalyzed Decarboxylation of 6-Nitrobenzisoxazole-3-carboxylate

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Abstract: Poly(vinylbenzo-18-crown-6) (P18C6) dissolved in water acts as a neutral polysoap and effectively catalyzes the decarboxylation of 6-nitrobenzisoxazole-3-carboxylate through transfer of the substrate into the aromatic inner core of the tightly coiled polymer. The bound carboxylate decomposes 2300 times faster than in water. The intrinsic binding constant of the anionic solute is vastly increased by adding crown complexable cations. This converts the neutral polysoap into a polycation. The effectiveness of cations in enhancing the binding is $Cs^+ > K^+ \gg Na^+ \gg Li^+$. The most effective system is P18C6-CsCl where bound carboxylate at 25 °C decomposes 14 000 times faster and at 5 °C 86 000 times faster than in water, a significant improvement over other polysoaps. The aromatic hydrocarbon environment and the high charge density of polysoap are believed to be the main factors contributing to the high catalytic activity of this system. Hydrophobic anions such as BPh_4^- and picrate are effective inhibitors by competing with the carboxylate for binding sites.

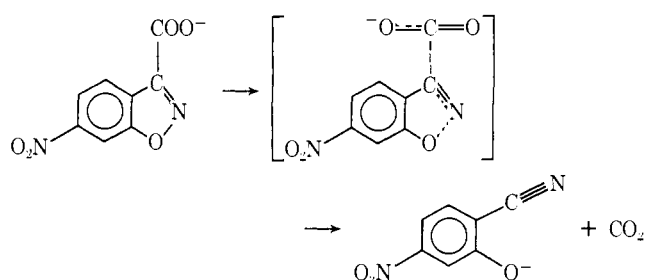
Poly(vinylbenzo-18-crown-6), abbreviated in this paper as P18C6, strongly interacts with a variety of organic solutes when dissolved in water.¹⁻³ The polymer, its structure depicted below, exhibits inverse temperature solubility in water, the cloud point being 37 °C. The low intrinsic viscosity (for $M_n = 106\ 000$, $[\eta]_0$ at 25 °C in water is only 0.107 as compared to 0.37 in $CHCl_3$) suggests that the macromolecule is in a



tightly coiled conformation resembling a nonionic micelle or neutral polysoap and stabilized at the polymer-water interface by water molecules hydrogen bonded to the crown ether oxygen atoms. Hydrophobic interactions cause the organic solutes to solubilize into the apolar polystyrene core of the polysoap. Moreover, binding of anionic solutes can be greatly augmented by means of crown ether complexable cations⁴ since the neutral poly(crown ether) now converts into a cationic polysoap.

The solute binding property of poly(vinylbenzo-18-crown-6)

induced us to evaluate its effectiveness to catalyze solvent-sensitive reactions. Such a reaction is the decarboxylation of benzisoxazole-3-carboxylate or that of its derivatives, studied in great detail by Kemp et al.⁵⁻⁷ Its decomposition into the salicylonitrile salt (the 6-nitro derivative of the carboxylate was used in our study) was shown to be a concerted intermediateless E_2 elimination,⁶ slow in water and other protonic solvents, but



accelerated in media such as benzene and tetrahydrofuran, and extremely fast in dimethyl sulfoxide or hexamethylphosphoramide, the rate constant in the latter solvent being larger than that in water by a factor of 10^8 . The solvent effects were rationalized in terms of stabilization or destabilization of the anionic reactant or its charge delocalized transition state. Catalysis can also be accomplished by means of cationic or neutral micelles, e.g., cetyltrimethylammonium bromide.⁸⁻¹¹ The latter study, in particular, led us to investigate in more

detail the effects of added P18C6 on the decomposition of these carboxylates, the preliminary results of which were reported earlier.^{1,2} The reaction is a convenient one as the formation of the product can easily be monitored spectrophotometrically. Moreover, the decomposition is a clean unimolecular process which facilitates interpretation of the kinetic data.¹⁰ Since the reaction is carried out in a neutral medium, catalyzed by hydrophobic and electrostatic interactions with P18C6, it can serve as a simple model for decarboxylations that are biologically of interest.

Recent publications by Klotz et al.¹² and by Kunitake et al.¹³ have demonstrated that chemically modified synthetic polymers acting as polysoaps can catalyze the decomposition of 6-nitrobenzoxazole-3-carboxylate (1) in water. The nitrogen-containing polymers were endowed with lauryl groups to augment the hydrophobic interaction of the substrate with the polymers, while quaternization of the nitrogen improved the binding of the anionic reactant through electrostatic attraction. In our work, catalysis by the homopolymer P18C6 in the presence of salts is also accomplished by a combination of hydrophobic and electrostatic interactions, the interesting and unique feature of this system being the cation specificity of the catalysis.

Experimental Section

Materials. The preparation of 6-nitrobenzoxazole-3-carboxylic acid has been reported.¹⁰ The melting point of the acid, obtained as the monohydrate, was 168–169 °C, in agreement with the literature value. The synthesis of vinylbenzo-18-crown-6 and its conversion to poly(vinylbenzo-18-crown-6) have also been described.¹⁴ A more convenient synthesis of the monomer using dihydroxybenzaldehyde as starting material was recently published.¹⁵ The number average molecular weight of the polymer as determined by high-speed osmometry was 42 000.

The lithium or sodium salt was prepared just prior to a kinetic experiment by dissolving a known quantity of the acid in water containing twice the required amount of the appropriate reagent grade hydroxide. The alkali chlorides and NaBPh₄ (Fisher) were reagent grade chemicals.

2-Cyano-5-nitrophenol, the decomposition product of 1, was prepared by dissolving 0.2 g of the carboxylic acid in 20 mL of an acetone–water mixture (9:1 by volume) containing a small amount of KOH. The decarboxylation is quantitative and is completed in less than 10 min. The solution is acidified with HCl and extracted with chloroform and the organic layer dried on Na₂SO₄. The phenol is recovered after evaporation of CHCl₃, mp 160 °C (lit.¹⁶ 160 °C).

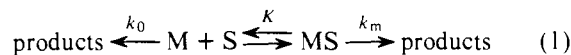
Kinetic Measurements. The decarboxylation of 1 was studied between 5 and 25 °C. In a typical experiment, 2 mL of a solution containing the required amount of acid, twice the amount of NaOH, and, if needed, a predetermined quantity of salt was placed in a 1-cm water-jacketed optical cell and rapidly mixed with a 1-mL solution of P18C6 of known concentration. The formation of 2-cyano-5-nitrophenolate was followed in a Cary 15 spectrophotometer by monitoring the absorption peak of the product in the 395–435-nm region. The absorption maximum of the phenolate varies with the experimental conditions (see Results and Discussion). The temperature was maintained to about 0.1 °C by means of a Haake FJ circulating bath. First-order rate constants were calculated from the expression $k = (1/t) \ln [a_\infty / (a_\infty - a_t)]$, where a_t and a_∞ refer to the optical densities at time t and $t = \infty$, respectively.

Results

The spontaneous but slow decarboxylation of 6-nitrobenzoxazole-3-carboxylate in water ($k = 3 \times 10^{-6} \text{ s}^{-1}$ at 25 °C) is accelerated on addition of P18C6 as evidenced by the rapid appearance of the yellow colored decomposition product, 2-cyano-5-nitrophenolate. We reported earlier^{1–3} that P18C6 in water exhibits a strong affinity for organic solutes. Therefore, the rate enhancement can best be interpreted by postulating a transfer of the carboxylate from the aqueous phase into the polymer domain. This process most likely is accompanied by dehydration of the substrate, analogous to that found on

binding picrate salts to P18C6. In the latter system the picrate absorption maximum changes from 355 nm (characteristic in protonic solvents such as water and alcohols) to 384 nm, close to the absorption maximum of a free picrate anion or that of a loose ion pair in solvents such as acetone or tetrahydrofuran.^{1–3} When completely transferred, 1 is expected to decompose at a rate comparable to that in a solvent whose polarity is close to that of the polymer domain, e.g., benzene.

The P18C6-catalyzed decarboxylation resembles a micellar catalysis. Such a reaction can be expressed in the familiar way:¹⁵



where M, S, and MS refer to the respective concentrations of free micelles and free and bound substrate, K denotes the binding constant of substrate to micelle, and k_0 and k_m are the rate constants of the substrate reacting in water and in the micelle, respectively. The quantity M in our system refers to the concentration of free “binding sites”, and is given by $[M] = [C]/N$ (i.e., K is defined for C/N), where C is the concentration of free crown monomer units and N is the average number of crown units needed to bind one carboxylate anion.

The observed rate constant k_ψ is given by $k_\psi = k_0 F_0 + k_m F_m$, the decarboxylation being pseudo-first-order if the fraction, $F_m = KC/(1 + KC)$, of carboxylate bound to P18C6 is constant. This is the case when a small fraction of binding sites is occupied. It can easily be shown¹⁷ that

$$\frac{1}{k_\psi - k_0} = \frac{1}{k_m - k_0} + \frac{N}{(k_m - k_0)KC} \quad (2)$$

assuming that N and k_m are not affected by already bound substrate. This assumption appears to be justified for N as long as the polymer chain does not take up cations.³ For example, picrate binding to neutral P18C6 (and also binding of methyl orange) can be accurately described by a rearranged form of the Langmuir isotherm, $1/r = 1/nKa + 1/n$,^{1–3} where r denotes the ratio of bound picrate to total crown monomer units, a is the free picrate concentration, and $1/n = N$ denotes the average number of crown monomer units needed to bind one solute molecule, i.e., it represents the size of the binding site. The linearity of the $1/r$ vs. $1/a$ plots implies that bound picrate anions do not affect succeeding bindings of this anion.

The validity of eq 2 was verified by measuring the decarboxylation rate constants, k_ψ , at constant carboxylate concentration ($S_0 = 5 \times 10^{-4} \text{ M}$) and varying [P18C6] between 1×10^{-3} and $7.5 \times 10^{-2} \text{ M}$. Two of the rate plots are shown in Figure 1. In the absence of cation binding to P18C6 the reaction is first order in carboxylate up to at least 70% substrate conversion, implying that only a small fraction of binding sites are occupied. Values for the binding constant at 25 °C (see below) show that for a P18C6 to carboxylate ratio of 50 and for $N = 40$ this fraction amounts to 0.12. However, it increases to about 0.35 at 5 °C for the same crown to substrate ratio, and even more sites are occupied when the polymer is charged. In the presence of KCl deviation from first-order kinetics already occurs below 70% conversion (see Figure 1), since the condition of a constant fraction of bound species, F_m , necessary for obtaining first-order kinetics cannot be maintained as the conversion proceeds. Another cause for the retardation is the binding of product, a problem neglected in the derivation of eq 2. Evidence for association of 2-cyano-5-nitrophenolate to P18C6 comes from the observed bathochromic shift in the absorption maximum of this compound on addition of the poly(crown ether). Such a shift was also reported by Klotz et al. in their catalysis studies with polyethylenimine polymers.¹² During a kinetic run the fraction of phenolate bound to P18C6

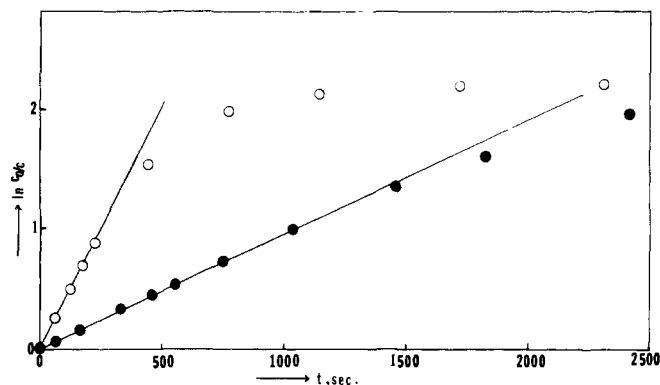


Figure 1. Plots of $\ln c_0/c$ vs. t for decarboxylation of 6-nitrobenzisoxazole-3-carboxylate (5×10^{-4} M) in water in the presence of P18C6 (2.5×10^{-2} M crown monomer units). (●) no salt present; (○) 10^{-2} M KCl.

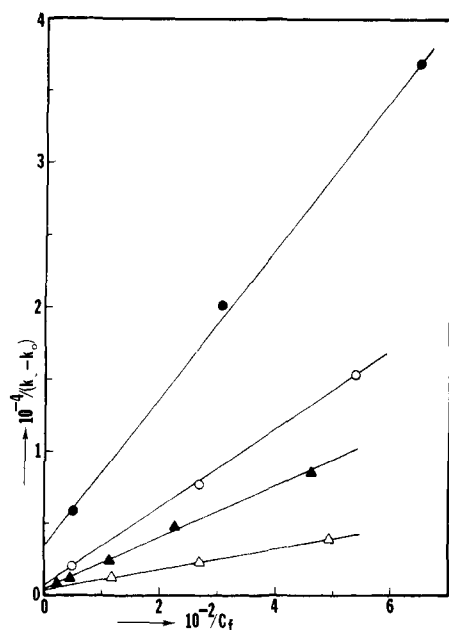


Figure 2. Plots of $1/(k_\psi - k_0)$ vs. the reciprocal concentration, $1/C_f$, of free crown monomer units (see eq 2) [sodium carboxylate] = 5×10^{-4} M. (▲) 25 °C; (○) 15 °C; (●) 5 °C; (Δ) 25 °C, but with 10^{-3} M KCl.

does not change much; therefore, λ_m does not significantly shift with reaction time. However as [P18C6] is increased from one run to the next, the λ_m shifts to higher wavelength. Product binding to P18C6 will be discussed later in more detail. Because of the observed deviations from first-order kinetics, initial rate constants were used in checking the validity of eq 2.

Plots of $1/(k_\psi - k_0)$ vs. $1/[P18C6]$ for sodium carboxylate at different temperatures are depicted in Figure 2. The rate constants k_0 were calculated from the known k_0 at 30 °C and the activation energy of the reaction $E = 32$ kcal/mol.⁶ The values are $k_0 = 0.3 \times 10^{-5}$ (25 °C), 0.046×10^{-5} (15 °C), and 0.0064×10^{-5} s⁻¹ (5 °C), all being small compared to k_ψ . The free crown concentration $C = [P18C6]$ can be computed from the expression $C = C_0 - k_\psi S_0 N / k_m$. Here, k_ψ / k_m is the fraction of carboxylate molecules bound ($k_0 \ll k_m$), and $S_0 N$ equals the concentration of crown units needed to bind all substrate molecules. N and k_m are unknowns, but the ratio N/k_m needed to calculate C can be determined in a different set of experiments as discussed below.

Figure 2 reveals that the slope for the potassium salt is considerably smaller. This is caused by K^+ binding to P18C6 which at 10^{-3} M KCl is already large enough to electrostatically

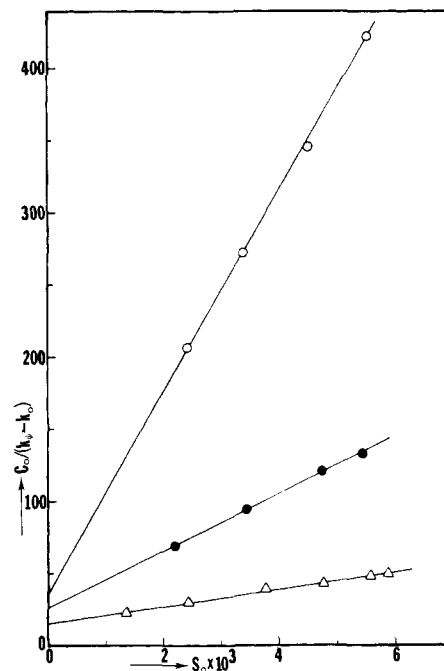


Figure 3. Plots of $C_0/(k_\psi - k_0)$ vs. S_0 (see eq 4). $[C_0]$ = total concentration of crown monomer base units = 2.5×10^{-3} M; S_0 = total carboxylate concentration. (Δ) 25 °C; (●) 15 °C; (○) 5 °C.

cally enhance the carboxylate binding. Also, the intercepts are too small to arrive at accurate k_m values which are needed to determine the intrinsic binding constants, K . The latter cannot be measured directly as the carboxylate decomposes too fast in the presence of P18C6.

To obtain further information on K and k_m , a second series of experiments was carried out choosing conditions such that $S_0 \gg C_0/N$, i.e., the carboxylate concentration far exceeds the available binding sites. Application of the steady state for reaction 1 leads to the following relationship¹³

$$(k_\psi - k_0) = k_m C_0 / (K + S_0) N \quad (3)$$

which can be rearranged to read

$$C_0 / (k_\psi - k_0) = N / k_m K + N S_0 / k_m \quad (4)$$

where the variables and constants have the same meaning as before. In these experiments [P18C6] is kept constant at 2.5×10^{-3} M and S_0 is varied between 1×10^{-3} and 6×10^{-3} M. The lithium salt of the carboxylate was used to ensure that no cations bind to P18C6 at the higher substrate concentrations used in these runs. Assuming that the size of the binding site is not much different from that found for picrate, i.e., $N \approx 40$, the condition $S_0 \gg C_0/N$ appears to be fulfilled since $C_0/N \approx 6 \times 10^{-5}$ M.

Plots of $C_0/(k_\psi - k_0)$ vs. S_0 at 25, 15, and 5 °C are depicted in Figure 3, correlation coefficients being better than 0.997. The intrinsic binding constants can be computed from the slopes and intercepts of these plots or by combining the slope $N/k_m K$ of eq 2 with the slope N/k_m derived from eq 4 (k_0 is negligibly small as compared to k_m). The respective $N/k_m K$ and N/k_m values are collected in Table I. The ratio N/k_m was used to calculate the free P18C6 concentration C , a variable needed in the first set of experiments to plot eq 2.

The agreement between the two sets of $N/k_m K$ values is gratifying, especially at 25 and 15 °C. The intercept values are more sensitive to experimental error than those derived from the slopes, especially when the latter are steep, e.g., at 5 °C. Therefore, the binding constants as listed in Table I were calculated from the two slopes $N/k_m K$ and N/k_m . The accuracy

Table I. Intrinsic Binding Constants and Decarboxylation Rate Constants for 6-Nitrobenzoxazole-3-carboxylate^a Bound to Poly(vinylbenzo-18-crown-6)

Temp, °C	[KCl] × 10 ³ , M	[CsCl], M	$N/k_m K$, ^b M s	$N/k_m K$, ^c M s	N/k_m ^d × 10 ⁻⁴ , s	k_m × 10 ⁴ , s ⁻¹	K , M ⁻¹
5			52.2	36.1	70.5	5.96	1350
5		0.2				55	
15			27.3	26.2	19.7	21.3	720
15		0.2				154	
25			17.8	15.2	6.1	69	340
25		0.2				420	
25	0.50			8.11	5.86	60	610
25	1.00			4.86	3.78	92	780
25	2.00			1.50	3.94	89	~2500
25	4.00				3.17	110	

^a Sodium or lithium salt was used; see text. ^b Slope of plot from eq 2, Figure 2. ^c Intercept of plot from eq 4, Figures 3 and 6. ^d Slope of plot from eq 4, Figures 3 and 6.

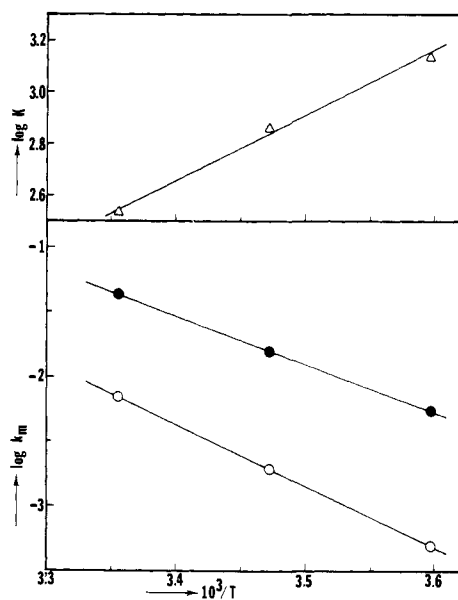


Figure 4. (Δ) Plot of $\log K$ (intrinsic binding constant in the absence of salt) vs. $1/T$ for 6-nitrobenzoxazole-3-carboxylate binding to P18C6 in water; (O), (\bullet) activation energy plots for decomposition of carboxylate bound to P18C6 in the absence of salt and in the presence of 0.2 M CsCl, respectively.

of the K values is estimated to be within 10%. The van't Hoff plot shown in Figure 4 gives for this hydrophobic interaction a $\Delta H^\ddagger = -11.3$ kcal/mol and $\Delta S^\ddagger = -26$ eu.

A direct measurement of k_m in the absence of salt is difficult owing to the rather low binding constants. However, reasonable k_m values can be obtained from the slope N/k_m by assuming N for 1 to be the same as for the picrate anion. This assumption will be justified from experiments discussed later. Binding studies for picrate anions give directly a value of N ,³ and a plot of N vs. T yields $N = 42$, 37, and 34 at 25, 15, and 5 °C, respectively. The calculated $10^4 k_m$ values at these temperatures are 69, 21.3, and 5.96 as compared to the $10^4 k_0$ values of 0.03, 0.0046, and 0.00064, all in s⁻¹. The activation energy plot, depicted in Figure 4, gives $\Delta H^\ddagger = 21.1$ kcal/mol and $\Delta S^\ddagger = 2.3$ eu. Kemp's values in water are $\Delta H^\ddagger = 32$ kcal/mol and $\Delta S^\ddagger = 19$ eu.⁶ (Bunton reports for the reaction in water $\Delta H^\ddagger = 29.4$ kcal/mol and $\Delta S^\ddagger = 15$ eu.¹⁰)

Effect of Cation. The intrinsic binding constants of anionic solutes to P18C6 are enhanced on addition of K^+ and especially Cs^+ cations. For example, at 25 °C the K for picrate increases by a factor of 24 on addition of 0.002 M CsCl. Hence, k_ψ is expected to increase on addition of KCl or CsCl, and may reach the value k_m if all substrate can be bound.

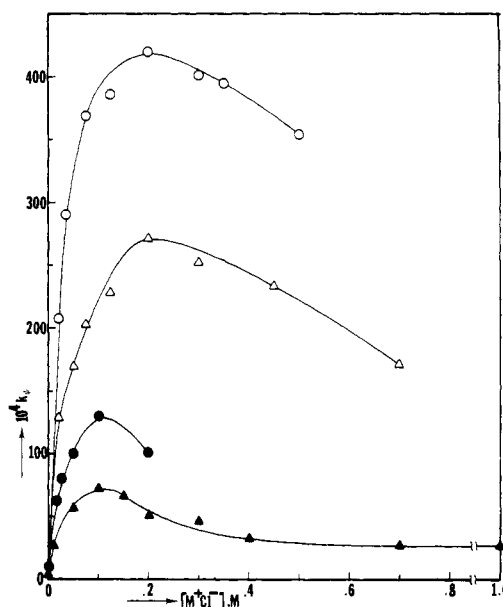


Figure 5. Plot of the observed rate constant, k_ψ , of decarboxylation of 6-nitrobenzoxazole-3-carboxylate in water in the presence of P18C6 as a function of KCl or CsCl concentration and at different ratios $r = [P18C6]/[carboxylate]$; $T = 25$ °C; (O) CsCl, $r = 50$; (Δ) CsCl, $r = 20$; (\bullet) KCl, $r = 50$; (\blacktriangle) KCl, $r = 20$.

Plots of k_ψ vs. salt concentration at different P18C6/1 ratios are shown in Figure 5. The increase is especially pronounced with CsCl. With $N < 40$, complete carboxylate binding is only realized at P18C6/1 ratios > 40 . A ratio of 50 was chosen in these experiments, and it is assumed that with CsCl all substrate is bound when k_ψ has reached its maximum value. The assumption appears reasonable since binding of the phenolate product to P18C6 is complete at 0.1–0.2 M CsCl, and its binding constant is comparable with that of the carboxylate, at least in the absence of salt. Note that for Cs^+ cations the maximum k_ψ value (assumed to be k_m) is 420×10^{-4} s⁻¹, 14 000 times larger than k_0 and about 6 times larger than the k_m of neutral P18C6.

Using the same conditions, k_m at 15 and 5 °C were found to be 154×10^{-4} and 55×10^{-4} s⁻¹ (see Table I). The activation energy plot shown in Figure 4 yields $\Delta H^\ddagger = 16.1$ kcal/mol and $\Delta S^\ddagger = -10.7$ eu.

Below a P18C6/1 ratio of 40 saturation of binding sites may occur, and the maximum k_ψ value, again reached at about 0.2 M CsCl, is given by $k_\psi(\max) = k_m r / N$, r being the P18C6/1 ratio. Experiments under these conditions provide information about N . At 0.2 M CsCl the observed rate constants at P18C6/1 ratios of 50, 20, 10, and 5 are $10^4 k_\psi$ (in s⁻¹) = 420,

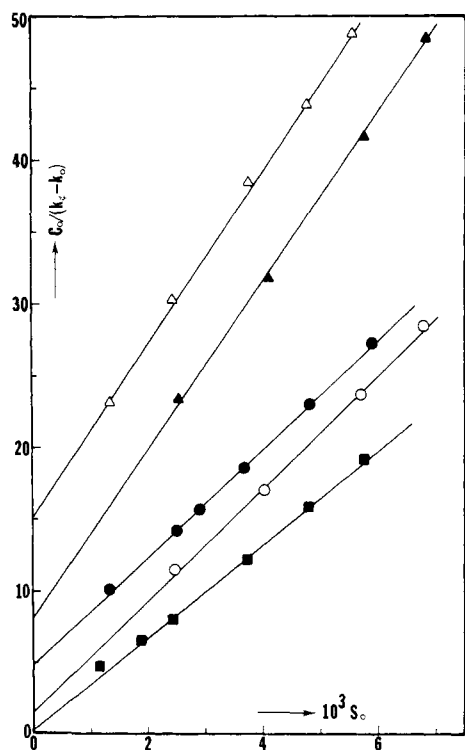


Figure 6. Plots of $C_0/(k_\psi - k_0)$ vs. S_0 as a function of charge density (i.e., at a constant P18C6/KCl ratio). $T = 25^\circ\text{C}$. $C_0 = [\text{P18C6}]_0 = 2.5 \times 10^{-3}\text{ M}$: (Δ) No KCl present; (\blacktriangle) 0.0005 M KCl; (\bullet) 0.001 M KCl; (\circ) 0.002 M KCl; (\blacksquare) 0.004 M KCl.

273, 147, and 79, respectively. This gives $N = 29 \pm 1.5$, assuming $k_\psi = k_m$ at $r = 50$, and compares with $N = 30$ for picrate binding at 0.2 M KCl and $N = 28$ at 0.2 M CsCl. The nearly identical values of N for the two solutes constitute the basis for our previous assumption that also in the absence of salt the N for 1 is the same as for picrate. For the latter solute N depends on the charge density, decreasing from 42 in the absence of salt to 28 at 0.2 M CsCl. This decrease in the size of the binding site was also found for methyl orange³ and for the phenolate product. For the latter anion $N = 26$ at 0.2 M CsCl.

Studies with KCl (see Figure 5) reveal that the maximum k_ψ is reached at 0.1 M KCl, but its value is at least three times lower than that for CsCl, i.e., $k_{\psi\text{max}} = 130 \times 10^{-4}\text{ s}^{-1}$ at 25°C . Under saturation conditions, with $r = 20$ and 10, $k_\psi = 73 \times 10^{-4}$ and $35.5 \times 10^{-4}\text{ s}^{-1}$, respectively, giving $N = 35$. To determine the effect of increased Cl^- concentration experiments were carried out in the presence of LiCl. With $r = 50$ and at 0.2 M CsCl, addition of 0.3 M LiCl decreased k_ψ from 420×10^{-4} to $380 \times 10^{-4}\text{ s}^{-1}$. At 0.5 M CsCl in the absence of LiCl k_ψ was found to be $350 \times 10^{-4}\text{ s}^{-1}$. With 0.1 M KCl and $r = 20$, addition of 0.9 M LiCl decreased k_ψ from 73×10^{-4} to $55 \times 10^{-4}\text{ s}^{-1}$. At 1 M KCl without LiCl k_ψ drops to $28 \times 10^{-4}\text{ s}^{-1}$. These results suggest that the high K^+ concentration rather than the high Cl^- content appears to be the principal cause for the decrease in k_ψ at high $[\text{KCl}]$.

In principle, the rate constant, k_m , of bound carboxylate can be determined as a function of charge density (i.e., at different ratios of total crown to bound cation) by varying the carboxylate concentration at constant $[\text{P18C6}]$ and $[\text{KCl}]$. Under these conditions the fraction of bound cation remains constant. Data were collected at 0.0005, 0.001, 0.002, and 0.004 M KCl using the lithium salt of 1. The respective $C_0/(k_\psi - k_0)$ vs. S_0 plots are shown in Figure 6 and the pertinent data given in Table 1. Although linear relationships are obtained, the rapid increase of K with $[\text{KCl}]$ renders determination of this constant

more difficult owing to the inaccuracy in the intercept $N/k_m K$. The k_m values, based on $N = 35$ found for picrate at 10^{-3} M KCl, are also somewhat erratic (the value at $5 \times 10^{-4}\text{ M}$ KCl appears to be too low), although an increasing trend can be noted at higher KCl concentration and charge density. Since the behavior with KCl appears to be more complex, the use of CsCl may give better results.

The phenolate product of the reaction also binds to the polymer, causing retardation as more product accumulates. The binding can be measured spectrophotometrically from the absorption spectra of the phenolate in water ($\lambda_m = 397.5\text{ nm}$, $\epsilon_m = 2570$) and of the bound species ($\lambda_m = 433\text{ nm}$, $\epsilon_m = 2790$). The latter spectrum was obtained in the presence of 0.2 M CsCl. Preliminary measurements yield $K \approx 500\text{ M}^{-1}$ at 25°C , comparable with that of the carboxylate. The binding rapidly increases on addition of CsCl to about $K = 3000\text{ M}^{-1}$ at $1.6 \times 10^{-3}\text{ M}$ CsCl. Temperature-dependent studies indicate an enhancement in the exothermicity of the reaction as the charge density increases.

Large organic anions such as tetraphenylboron or picrate anions effectively compete with the carboxylate for binding sites, and minute quantities of these solutes inhibit the decarboxylation. For example, with P18C6/1 = 50 and $[1] = 5 \times 10^{-4}\text{ M}$, the presence of $5 \times 10^{-4}\text{ M}$ NaBPh₄ decreases k_ψ at 25°C from 9.8×10^{-4} to $1.56 \times 10^{-4}\text{ s}^{-1}$. At a 10:1 P18C6/1 ratio, 10^{-4} M sodium picrate changes k_ψ from 39.7×10^{-4} to $1.1 \times 10^{-4}\text{ s}^{-1}$. Although the phenolate product, when added before the start of a decarboxylation reaction, also slows down the reaction, its low binding constant makes it a far less effective inhibitor than BPh₄⁻ or picrate.

Discussion

While differing in a number of details, micellar and polysoap catalysis of the decarboxylation of 6-nitrobenzoxazole 3-carboxylate basically involves the transfer of substrate from water to a more active environment. In micellar catalysis added electrolytes may alter the critical micelle concentration or the aggregation number of the micelle. These problems do not occur with polysoaps, although variables such as temperature and ionic strength affect the polymer conformation, and, therefore, the micellar properties of the polysoap. The polymers that have proven to be the most effective binders of organic solutes in aqueous media are those that were modified by addition of apolar side groups to enhance their hydrophobicity.^{12,13,18} For anionic solutes the binding can be further enhanced electrostatically by charging the polymer, often accomplished by quaternization of nitrogen present in the polymer chain.^{12,13} The polymer used in our studies is a well-characterized neutral homopolymer with no added apolar side chains but capable of strong hydrophobic interactions with a variety of organic solutes.^{2,3} It can easily be converted into a cationic polysoap of variable charge density, and the catalysis of 1 becomes cation specific since the stability of the cation-crown complex is cation dependent.

At 25°C , the intrinsic binding constant of 1 to neutral P18C6 is about 4 times lower than that for the picrate anion, largely due to a lower binding entropy. For picrate $\Delta H = -11.9\text{ kcal/mol}$, only slightly more exothermic than for 1, but ΔS is -17 eu as compared to -26 eu for the carboxylate. van der Waals forces are believed to contribute to the strong exothermicity of picrate binding to P18C6³ and similar interactions may cause the low ΔH value for 1. Differences between the carboxylate and picrate in degree of hydration, polarizability, charge delocalization, and size all may contribute to the different behavior of the two anions. Some correlation may exist between the binding constants and the solvent activity coefficients of anion transfer from water to aprotic solvents.¹⁹ Data for such coefficients are scarce for solvents with a polarity

comparable to that of the inner core of P18C6. A more systematic determination of anion binding to neutral polysoaps such as P18C6 may be useful in providing some insight into factors controlling anion solvation in media with aromatic hydrocarbon character.

The carboxylate, bound to the neutral polymer, decomposes at 25 °C 2300 times faster than in water. The activation parameters, $\Delta H^\ddagger = 21.1$ kcal/mol and $\Delta S^\ddagger = +2.3$ eu, are close to those reported by Bunton et al. ($\Delta H^\ddagger = 21.3$ kcal/mol, $\Delta S^\ddagger = -2.7$ eu) for decomposition of 1 bound to cetyltrimethylammonium bromide.⁹ The latter data, referring to a cationic micelle, should actually be compared with those obtained for charged P18C6 (see below). Carboxylate dehydration on transfer of 1 from water to P18C6 can account for the considerable decrease in ΔH^\ddagger and ΔS^\ddagger . Data on picrate binding to P18C6 suggest that this anion is present in the inner core of the neutral P18C6 micelle as a free dehydrated anion. If this is true also for 1, then dehydration will destabilize the charge delocalized transition state of 1 to a lesser extent than its initial state, thereby lowering ΔH^\ddagger .⁶ At the same time ΔS^\ddagger is expected to approach zero since the unimolecular reaction occurs in a low polarity environment with charge being conserved in the transition state and with structural differences between initial and transition state expected to be small.⁶

Compared with the 24 solvents studied by Kemp and Paul,⁶ our k_m for 1 bound to P18C6 approaches the decarboxylation rate constant reported in benzene. Converting the acid with tetramethylguanidine as base into a benzene-soluble salt, Kemp and Paul found the rate constant to vary somewhat with base concentration, the highest one being k (25 °C) = $50 \times 10^{-4} \text{ s}^{-1}$. The authors stress that their values probably represent lower limits as ion pairing is likely to occur in benzene. Nevertheless, the closeness to our k_m value of $69 \times 10^{-4} \text{ s}^{-1}$ is striking, and reinforces our suggestion that 1 is present in the inner core of the P18C6 polysoap, surrounded by benzene moieties. The rate constants in ether and glyme type solvents are considerably higher, varying from $2 \times 10^{-2} \text{ s}^{-1}$ in dioxane (25 °C) to 2.5 s^{-1} for diglyme (25 °C).

The aromatic environment provided by the P18C6 molecule is probably responsible for the high catalytic efficiency of the binding sites. For the nonquaternized laurylated polyethylenimine (containing one lauryl group per four nitrogen atoms)¹² the k_m/k_0 ratio is 220 as compared to 2300 for neutral P18C6. The aliphatic hydrocarbon environment is apparently less effective in catalyzing the decarboxylation than the more polarizable P18C6 domain, but no data are available to compare reactivities in benzene with that in aliphatic hydrocarbons.

Although the k_m/k_0 ratio for neutral P18C6 is high, the intrinsic binding constant of 1 to the polymer at 25 °C is only 340 M^{-1} , as compared to about 10^4 for the nonquaternized polyethylenimine.¹² The higher binding constant for the latter polymer may partly be the result of electrostatic attraction in addition to hydrophobic interactions since some lauryl groups must be attached to a quaternary nitrogen. It is interesting to note that full quaternization with CH_3 or C_2H_5 increases the intrinsic binding constant by only a factor of 2.¹² In our system the binding efficiency is vastly improved by adding K^+ or Cs^+ cations to P18C6.³ Therefore, the increase in k_ψ shown in Figure 5 chiefly results from a rapid increase in the fraction of bound carboxylate as more cations complex with the poly-crown ether. However, k_ψ for the CsCl -P18C6 system eventually reaches a value six times greater than the k_m found for neutral P18C6. Hence, the higher catalytic efficiency of charged P18C6 results not only from enhanced substrate binding but also from a higher decarboxylation rate constant for substrate bound to a charged binding site.

The higher k_m of the Cs^+ charged polysoap results from a decrease in the activation enthalpy from 21.1 to 16.1 kcal/mol.

This is partially offset by a decrease in the activation entropy from +2.3 to -10.7 eu. Klotz et al. also found k_m to increase with charge density¹² but their effects are not purely electrostatic since alkyl groups are introduced into the polyethylenimine. For example, quaternization with CH_3 doubles the k_m , while C_2H_5 groups enhance k_m by a factor of 6.¹² In micellar catalysis the most effective catalyst was found to be a dicationic surfactant,¹⁰ although it is somewhat surprising that rate enhancements found on addition of certain additives to cationic soap micelles have been interpreted in terms of lowering of the charge density.¹⁰ Frequently, such additives involve aromatic compounds such as Igepal (an aryl polyether) or sodium tosylate, and it is plausible that they modify the micellar structure to produce a more aromatic, and, therefore, more reactive environment.

The higher catalytic constants found with charged polymers have been rationalized by assuming that the cationic environment stabilizes the charge delocalized transition state more than the initial state. It requires the delocalized charge to move closer to the positively charged crown complexes, resulting in loss of freedom and a lower ΔS^\ddagger .¹⁰ Verification of this suggestion awaits more information on the exact location of the bound carboxylate, but some evidence from NMR data in micellar catalysis renders such an explanation plausible.¹⁰ A more quantitative relationship between k_m and charge density would be desirable, but the results from experiments with KCl reported in Table I lack sufficient accuracy for a meaningful treatment of the data.

The dependence of k_ψ on the nature of the cation correlates with the cation effect on picrate binding to P18C6.³ The catalytic effects decrease in the order $\text{Cs}^+ > \text{Rb}^+ > \text{K}^+ \gg \text{Na}^+ \gg \text{Li}^+$, reflecting differences in the binding constants of the respective cations to P18C6, i.e., 1.2 for Na^+ , 35 for K^+ , and 110 M^{-1} for Cs^+ .^{3,20} Catalysis with Na^+ is not very effective, but at 0.1 M NaCl sufficient Na^+ binds to P18C6 to enhance k_ψ to $52 \times 10^{-4} \text{ s}^{-1}$, still considerably below the k_ψ for K^+ and Cs^+ . No effect on the rate is found with 0.1 M LiCl.

It is interesting to note that the maximum k_ψ for Cs^+ is about three times that for K^+ , and the drop in k_ψ at higher salt concentration is also less pronounced. The maxima occur at about 0.1–0.2 M salt (Figure 5). Based on the binding constants of K^+ and Cs^+ to P18C6, the maximum charge density should have been reached at this salt concentration. The main reason for the difference in behavior between K^+ and Cs^+ appears to be the extent of hydration of the bound cations. The K^+ cation forms a 1:1 complex with benzo-18-crown-6, but its binding constant to P18C6 is known to drop sharply as the ratio of bound K^+ to crown approaches 0.5.^{20–22} More cations can be forced on the chain by increasing $[\text{KCl}]$ to 1 M, but viscosity data³ indicate that under these conditions the polymer chain partially uncoils, probably owing to electrostatic repulsion and hydration of the bound K^+ cations. This unfolding of the chain either leads to release of solute molecules, or the bound solute itself may become partially hydrated. Preliminary dialysis experiments with picrate salts favor the latter possibility. Hence, in the catalysis experiment at high salt concentration bound carboxylate may become partially hydrated, leading to a decrease in k_ψ . On the other hand, hydration of bound Cs^+ is energetically less favorable than for K^+ . Moreover, Cs^+ is known to form a 2:1 crown-cation complex with benzo-18-crown-6. Such a complex is especially stable when crown ligands are spaced closely together such as in P18C6, and the ratio of bound Cs^+ to crown in the poly(crown ether) usually does not exceed 0.5.^{21,22} With Cs^+ sandwiched in between two ligands, hydration will be hindered. Also the two crown ligands complexed to Cs^+ may come from more distant points on the chain, and such "intramolecular cross-links" could also make polymer expansion more difficult. Hence, carboxylate hydration for a Cs^+ charged polymer is likely to be less pro-

nounced than for K^+ . The result is a higher k_{ψ} maximum and a slower drop in k_{ψ} at higher CsCl concentrations. For Rb^+ a k_{ψ} of $237 \times 10^{-4} s^{-1}$ was measured at 0.2 M RbCl, just in between that of Cs^+ and K^+ . The Rb^+ cation barely fits the crown cavity and some tendency to form 2:1 crown-cation complexes may exist.

Part of the decrease in k_{ψ} can be attributed to the high Cl^- content (see Results), possibly because the anions in the Stern layer lower the effective charge density at the binding sites. The effect is not large, confirming other observations that the carboxylate anion resides in the inner core of the poly(crown ether). It is also pertinent to mention that high concentrations of KCl or CsCl induce hypsochromic shifts in the spectra of P18C6 bound picrate and 2-cyano-5-nitrophenolate. Dialysis measurements show that these solutes remain bound to the polymer; hence hydration appears to be the cause of these shifts. They are more pronounced with KCl than with CsCl, confirming the above observations on the carboxylate reaction.

Inhibitory effects of large hydrophobic anions such as BPh_4^- and picrate derive from competition for binding sites. With BPh_4^- the initial decarboxylation rate constant is considerably smaller than the rate constant calculated in the later stages of the reaction. No satisfactory explanation for this observation has been found.

Finally, the maximum catalytic effect, k_m/k_0 , for the P18C6-CsCl system which reaches 14 000 at 25 °C and 86 000 at 5 °C compares very favorably with other systems. For monocationic detergents such as cetyltrimethylammonium bromide k_m/k_0 is about 100,¹⁰ for zwitterionic surfactants such as *N,N*-dimethyl-*N*-dodecylglycine¹¹ it reaches 170, and for dicationic detergents¹⁰ the ratio is about 400. With laurylated polyethylenimines the maximum effect is 1300 for the ethyl quaternized derivative,¹² while the imidazole and pyridine polymers of Kunitake et al.¹³, quaternized with alkyl substituents, yield as the highest value $k_m/k_0 \approx 350$.

Differences in k_m/k_0 between the polysoaps are chiefly caused by differences in the polarity of the inner core of the polysoap, the charge density at the binding sites, and the conformation of the polymer. The latter variable probably affects the location of the substrate relative to that of the po-

lysoap-water interphase. Apparently, an environment with aromatic character and high charge density provides an effective catalytic site, and in our system full binding can be achieved as long as the ratio of total crown monomer units to substrate exceeds 30, the size of the binding site in the presence of CsCl. It should be possible to construct other polymer structures with similar or more effective catalytic properties. Indeed, recent studies indicate that polystyrene with short glyme chains attached to the benzene moieties is also an effective catalyst, the substrate being bound by strong hydrophobic interactions.²³

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